Corrosion of Prestressing Steel in High Performance Grouts

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1 INTRODUCTION

Reinforced concrete as a combination of steel and concrete is one of the most widely used construction material. Combining advantages of two materials (high compression strength of concrete and high tensile properties of reinforcing steel) results in a material that can alone bare mechanical and environmental loading. For long period of time prestressed concrete structures were considered to be durable without any need of repair or later investments. Inspections of Croatian bridges have shown that due to aggressive, maritime conditions almost all of them have problems with chloride induced corrosion and that corrosion is the main reason for their reduced service life. As a result, the repair costs of these structures constitute a major part of the current spending on infrastructure and they often overhead the costs of structures themselves. The enormous costs and safety issues associated with corrosion of steel in concrete have resulted in the development of a wide range of new technologies and materials to increase the durability of concrete structures and their repairs.

Portland cement grout is used in post-tensioned and retaining structures to provide bond between the tendon/anchor and the surrounding concrete/ground and also to fill the voids between protective duct and prestressing strand which suppresses the flow of water and chloride ions [1, 2]. Grout is the last but most important corrosion protection layer in post-tensioned prestressed structures and with adequate materials, good design and high-quality installation of grout it is possible to minimize the risk of corrosion. Grout for bonded post-tensioning is a combination of Portland cement and water, along with different admixtures needed to obtain required properties. An optimum grout is considered the one that combines desirable properties in fresh and hardened state along with good corrosion protection.

The most common method today of decreasing and prevention of reinforcement corrosion is application of corrosion inhibitors, even though some of the research show their poor performance [3, 4]. An ideal inhibitor would be a compound preventing corrosion without unfavourable effects on the properties of the cementitious materials. In this research effectiveness of two commercial inhibitors were tested on steel electrodes when added into simulated pore solution and when added into grout mixture. The influence of corrosion inhibitors on mechanical properties of grout was evaluated as well.

2 EXPERIMENTAL PROGRAM

Since corrosion is an electrochemical reaction electrochemical techniques can be used to determine corrosion rate of steel in concrete.

In the first stage of this research accelerated corrosion testing was performed on electrodes made of black steel and electrodes made of prestressing steel in highly alkaline media, such as concrete pore solution with different concentrations of chloride ions [5-9]. The aim was to evaluate which concentration of chloride ions will surely cause corrosion initiation of black steel and prestressing steel, in other words which concentration of chloride ions is for given system the critical one. Before applying anodic potential for acceleration of corrosion open circuit potential was let to stabilize for 30 minutes and was measured every 10 seconds. After stabilization of corrosion potential, potentiodynamic anodic potential was impressed and the change of current was monitored. Table 1 shows variation of chloride ions concentration in both systems.

Type of steel	Chloride concentration (% of pore solution)				
Black steel	0,0	0,25	0,5	1,0	3,0
Prestressing steel	0,0	1,0	3,0	5,0	-

Table 1 Concentration of chloride ions

In the second stage of the research accelerated corrosion testing was performed in concrete pore solution with critical concentration of chloride ions and different concentration of two corrosion inhibitors. Both corrosion inhibitors are known on construction market and are recommended by their manufacturers for the use in cementitous materials. Inhibitor 1 is an organic-based admixture that does not contain any nitrite-based compounds. Inhibitor 2 is a combination of aminoalchols, and organic and inorganic inhibitors. Both inhibitors protect the anodic and cathodic area of the corrosion cell and are known as mixed inhibitors.

Testing was performed on black steel and prestressing steel to research the differences between two systems and to evaluate the efficiency of each inhibitor as a protection of steel when added directly into concrete pore solution [9]. Corrosion potential was measured for 30 minutes and then potentiodynamic anodic polarization was applied. Potentiodynamic polarization curves were obtained at a scan rate of 1,0 mV/s using a PAR VMP2 potentiostat. The current and potential were continuously recorded every 1 second using Ec-Lab sofware. Applied potential was rised from open circuit potential to 1 V into the anodic directon or until the increase in the current was observed. Table 2 shows variation of inhibitor concentration in both systems.

Type of steel	Type of inhibitor	Corrosion inhibitor concentration (% of pore solution) with 5 % of chloride			
Black steel	INH1	0,1	0,3	0,5	1,0
	INH2	0,1	0,3	0,5	1,0
Prestressing steel	INH1	0,1	0,3	0,5	1,0
	INH2	0,1	0,3	0,5	1,0

Table 2 Concentration of inhibitors

In the last and most important stage of the work corrosion testing was performed on prestressing steel rebar embedded in different high performance grouts. The aim was to evaluate the influence of grout quality (physical protection) and the influence of different admixtures (chemical protection) on corrosion prevention of the prestressing steel in grout [10-13]. Corrosion of prestressing steel in grout specimens was evaluated by impressing 10 V anodic potential for acceleration of corrosion. The effectiveness of the inhibitors and admixtures added to grout was evaluated by measuring current vs. time and time-to-cracking of the grout specimens. Since effective inhibitor is considered to be the one that prevents corrosion but does not have unfavourable effects on the properties of the concrete, mechanical properties (compressive strength) of grout were tested as well.

3 MATERIALS

3.1 PORE SOLUTION

Pore solution used in experiments was produced from early aged concrete [13]. The concrete paste was kept in a closed mould for 7 days without contact with air or water to avoid carbonation. In hardened state it was triturated until all of the powder passed through the sieve of 80 μm. Simulated pore solution was prepared with powder and distilled water in 1:10 ratio and after 2 h, this solution was filtrated through filter paper. The pH value of the filtrated solution was 12.4.

3.2 ELECTRODES

Two types of steel were used for preparation of working electrodes during the research. First type was black steel, the most common steel used in construction as reinforcement. Second type was high strength prestressing steel that has chemical composition in accordance with EN 10020 “Definition and classification of grades of steel”. From this two types of steel electrodes were constructed manually and were used as working electrodes. Small specimens of steel were connected to copper wire that was inside a glass tube. All sides of steel specimen were protected with 5 mm thick epoxy coating, except one unprotected side with area of 0.28 cm^2. After the epoxy coating had firmed, electrodes were mechanically abraded on 400, 600 and 1200 grade emery paper, then degreased with ethanol and rinsed in distilled water. These way prepared specimens were used in accelerated corrosion testing in pore solution. Working electrode is shown in Figure 1.

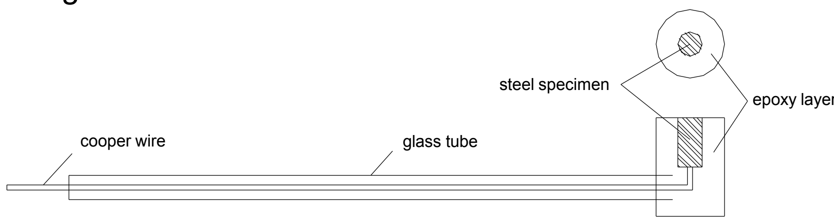


Figure 1 Manually prepared working electrode

Grout specimens with embedded steel were prepared in this way: 12 cm long prestressing steel bars were protected with thin layer of epoxy, except the area of 5 cm that was left unprotected. These steel specimens were embedded in 8 cm high and 7 cm thick moulds in which fresh grout was poured, Figure 2. Grout specimens prepared this way were left to cure for 28 days and then used in accelerated corrosion testing as well. All together 6 series were tested (12 specimens).

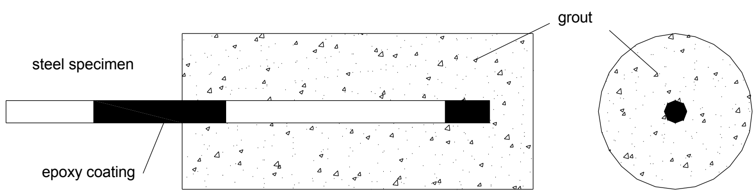


Figure 2 Grout specimens for corrosion testing

Counter electrode was graphite rod and reference electrode was saturated calomel electrode (SCE). All potentials reported in this research refer to SCE.

3.3 GROUT

Grout for bonded post-tensioning is a combination of Portland cement and water, along with different admixtures needed to obtain required properties. Two types of cement have been used:

1. Portland Cement 30% slag, Class 45, slow hydratation
2. Portland Cement Class 45, without slag, fast hydratation.

During experimental work grout specimens were prepared from high performance grout mixtures with different admixtures and different w/c ratio. Water/cement ratio was varied from 0.35 to 0.44. Admixtures used in this work were: superplasticizers (SP), corrosion inhibitors (INH), anti-bleeding (AB) and expansive (E) admixtures from 3 different admixtures manufacturers (admixtures labelled 1, 2 or 3 depending on manufacturers). All grout mixtures were tested according to EN 445 “Grout for prestressing tendons - Test methods” and are considered to be high performance grouts because they have satisfied all criteria from EN 447 “Grout for prestressing tendons - Specification for common grout”. Table 3 shows grout mix designs and admixtures used in this research.

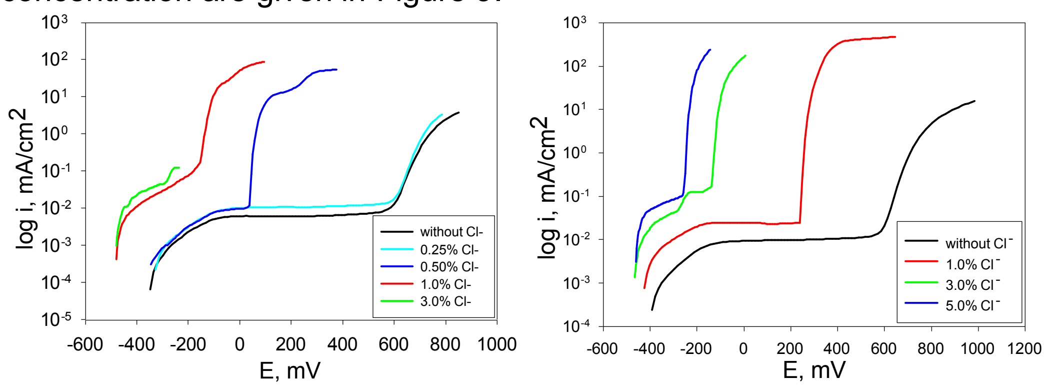
No.	w/c	Admixtures
1	0.44	-
2	0.40	1% E_2, 2% AB_2
3	0.35	0,35% SP_2
4	0.40	0,18% INH_1, 1% E_2
5	0.40	0,25%SP_2, 1% INH_2
6	0.40	0,2% SP_3, 1% E_3

Table 3 Grout mix designs

4 RESULTS AND DISCUSSION

4.1 STEEL IN PORE SOLUTION CONTAMINATED WITH CHLORIDES

Anodic polarization curves obtained for electrodes produced from black steel and prestressing steel in pore solution with different chloride concentration are given in Figure 3.



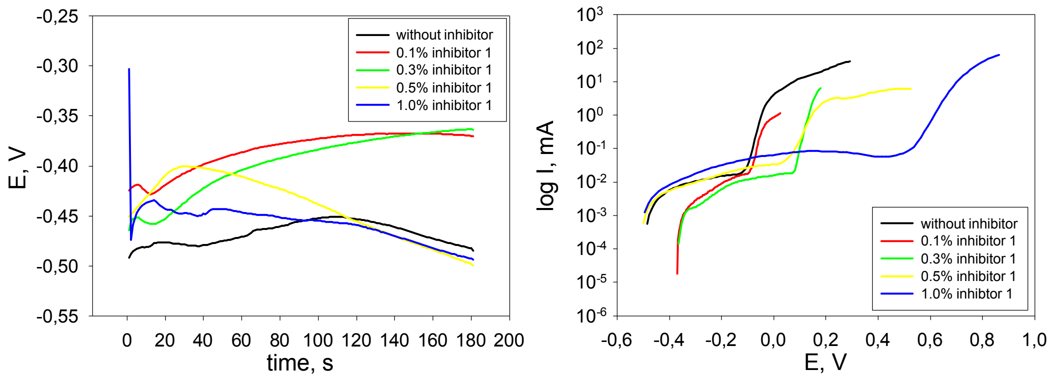
a) black steel b) prestressing steel

Figure 3 Potentiodynamic polarization curves for black and prestressing steel

From the results of potentiondynamic anodic polarization, that are given in Figure 3, it is evident that the resistance to chloride induced corrosion of prestressing steel is much higher than the resistance of black steel. While 0.5% of chloride ions caused pitting corrosion on black steel surface, it took 1% of chloride ions to do the same on surface of prestressing steel. To make sure the chlorides will induce corrosion 5% concentration was chosen as critical concentration of chloride for both black steel and prestressing steel.

4.2 INHIBITORS IN PORE SOLUTION CONTAMINATED WITH CHLORIDES

The efficiency of inhibitor 1 was first tested on black steel in pore solution with critical concentration of chloride ions (5%). Change of the open circuit potential (OCP) with time and change of current during potentiodynamic anodic polarization with different concentration of the inhibitor 1 are shown in Figure 4.

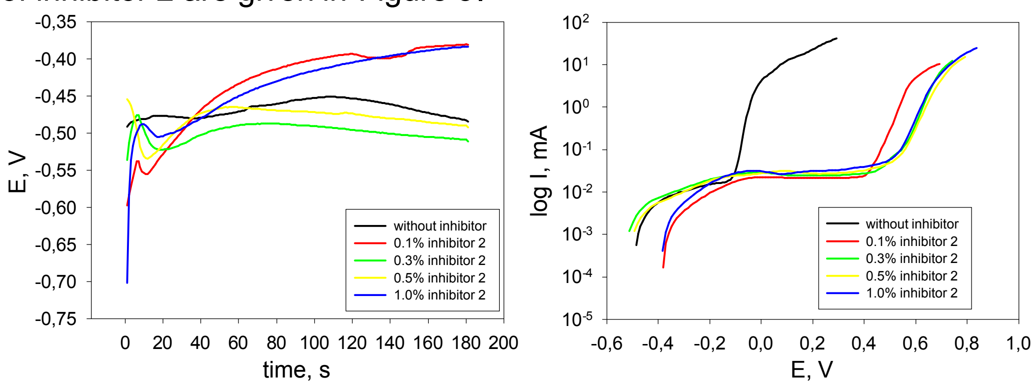


a) OCP b) polarization curve

Figure 4 OCP and polarization curve for black steel in pore solution with 5% of chloride ions and with different concentrations of inhibitor 1

The first diagram on Figure 4 (c orrosion potential vs. time) shows that lower concentrations (0.1% and 0.3%) of inhibitor 1 are causing the rise of corrosion potential. While corrosion potential of the sample without addition of the inhibitor was around -470mV, with the addition of 0.1% of inhibitor potential significantly shifted to the anodic direction, to the values around -350mV. On the other hand, when a larger concentration of inhibitor 1 was added corrosion potential rose at first but then started to shift into cathodic direction (-500mV). Some authors [14] are of opinion that the risk of corrosion is lower if corrosion potential tends to rise during the time. The second diagram on Figure 4 (current vs. potential) on the other hand shows that 1.0% concentration of inhibitor 1 is the most efficient; concentrations 0.5% and 0.3% have good efficiency whil e 0.1% is not efficient at all.

Results of accelerated corrosion testing of black steel in pore solution and with critical concentration of chloride ions (5%) with different concentration of inhibitor 2 are given in Figure 5.

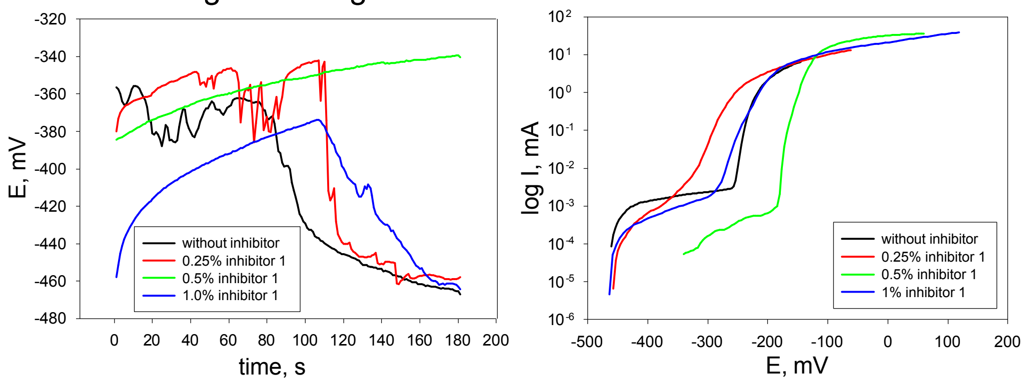


a) OCP b) polarizaton curve

Figure 5 OCP and polarization curve for black steel in pore solution with 5% of chloride ions and with different concentrations of inhibitor 2

The first d iagram on Figure 5 (corrosion potential vs. time) shows that addition of the inhibitor 2 into the system causes the increase of corrosion potential. Systems with lower or higher concentration of inhibitor 2 behave in the same manner. With the addition of inhibitor 2 corrosion potential starts from negative values (-650mV) and then rapidly shifts to the anodic direction. From the second diagram on Figure 5 (current vs. potential) it is evident that all concentrations of inhibitor 2 are efficient. Even the lowest concentration of inhibitor 2 (0.1%) prolongs passivity of black steel in pore solution contaminated with chlorides.

Results of testing prestressing steel in pore solution and with critical concentration of chloride ions (5%) together with different concentration of inhibitor 1 are given in Figure 6.

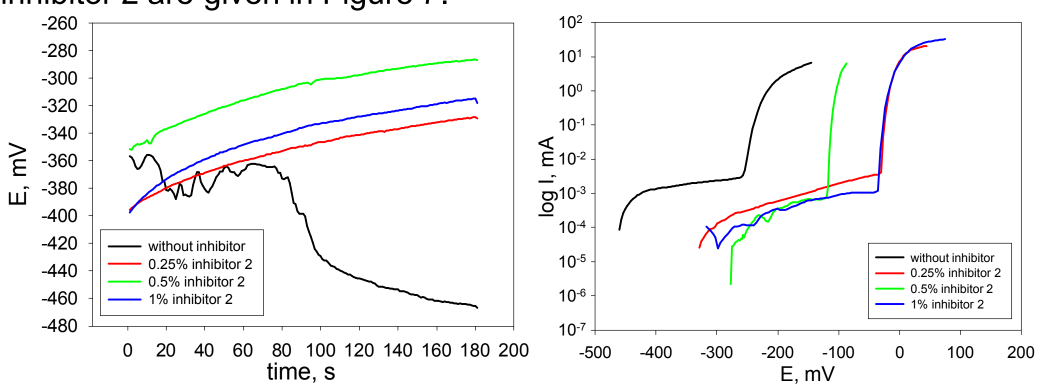


a) OCP b) polarization curve

Figure 6 OCP and polarization curve for prestressing steel in pore solution with 5% of chloride ions and with different concentrations of inhibitor 1

On the first diagram on Figure 6 (potential vs. time) it is evident that only concentration 0.5% of inhibitor 1 is efficient when it comes to chloride induced corrosion in alkaline environment. Only this concentration of inhibitor 1 caused the increase of corrosion potential to the anodic direction and forced the corrosion potential to stabilize. The same conclusion can be withdrawn from the second diagram on Figure 6 (current vs. potential). Only concentration 0.5% of inhibitor 1 managed to prolong the passivity of prestressing steel.

Results of testing prestressing steel in pore solution with the critical concentration of chloride ions (5%) together with different concentration of inhibitor 2 are given in Figure 7.



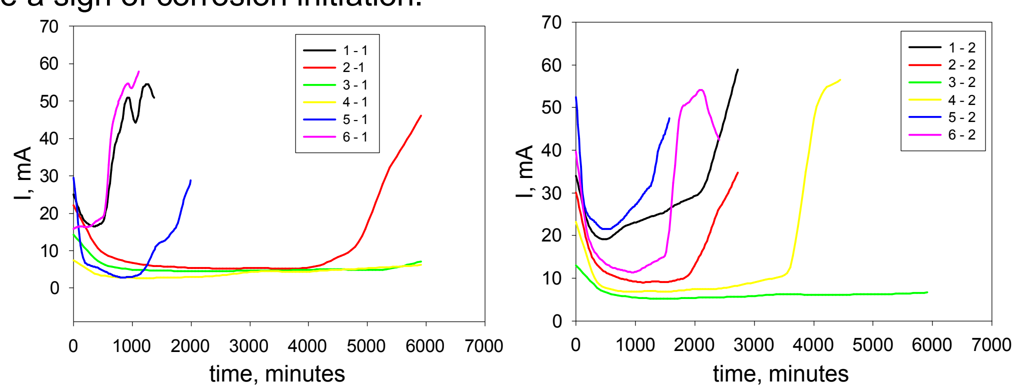
a) OCP b) polarizaton curve

Figure 7 OCP and polarization curve for prestressing steel in pore solution with 5% of chloride ions and with different concentrations of inhibitor 2

Inhibitor 2 showed efficiency on prestressing steel when added in all concentrations. Even addition of a very small amount of inhibitor 2 is causing significant rise of corrosion potential, which is shown on diagram OCP vs. time. Corrosion potential went from -460mV, without any addition of inhibitor, to -300 mV with the addition of 0.5% of inhibitor 2. Every single concentration of inhibitor 2 prolonged the passivity of prestressing steel when attacked by chloride ions in alkaline environment. Concentration of 1.0% of inhibitor 2 was again the most efficient.

4.3 STEEL EMBEDDED INTO HIGH PERFORMANCE GROUT

After the efficiency of two corrosion inhibitors was tested in pore solution contaminated with chlorides, accelerated corrosion testing was performed on prestressing steel embedded into high performance grout. Results of accelerated corrosion testing of prestressing steel embedded in grout are shown in Figure 8. Anodic potential of 10 V was applied and change of current in time was measured. Rapid increase of current is considered to be a sign of corrosion initiation.



a) testing 1 b) testing 2

Figure 8 Current during potentiostatic anodic polarization, grout specimens

Results show that specimens 2 (with expansive and anti-bleeding admixture), 3 (with superplasicizer) and 4 (with inhibitor 1 and expansive admixture) managed to preserve passivity of steel longer than other specimens. During the first testing the current of these specimens was stabile for 100 hours and the current of other specimens for 10 hours. During the second testing the current of specimens 3 and 4 was stabile for 67 hours, while the current of other specimens for 10 hours. This part of the research showed that grout with good durability properties, such as with low chloride diffusion coefficient, can withhold to corrosion attack longer even when no inhibitor is added. Figure 9 shows all specimens after accelerated corrosion testing.

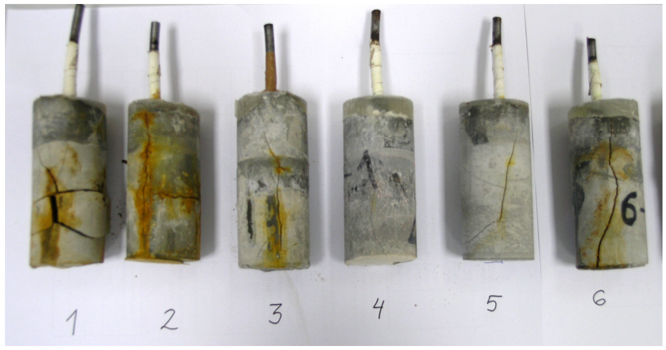


Figure 9 Grout specimens after potentiostatic anodic polarization

Mechanical properties of grouts were tested as well to ensure that addition of corrosion inhibitors does not affect strength of grout. Results of compressive strength testing are shown in Figure 10.

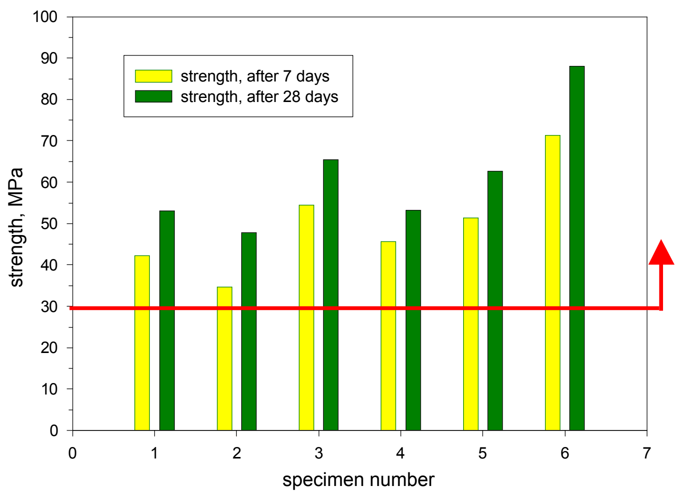


Figure 10 Compressive strength of grout

Testing of mechanical properties has shown that compressive strength is not critical issue and that addition of corrosion inhibitors is not harmful for mechanical properties of grout. Criteria for mechanical properties of the grout given in EN 447 “Grout for prestressing tendons - Specification for common grout”, that compressive strength should be more than 30 MPa, is satisfied by all grout mixes.

5 CONCLUSIONS

Corrosion inhibitors are the most common method today of decreasing the influence of chloride and prevention of reinforcement corrosion. There are many known types of corrosion inhibitors on the market but their efficiency is still not proven or thoroughly researched [3, 4]. Two corrosion inhibitors whose efficiency was researched in this paper have shown that they prolong passivity of black steel and prestressing steel when added directly to simulated pore solution. Inhibitor 1 showed best efficiency when added in concentration between 0.5% and 1.0% and inhibitor 2 in concentration 0.25%. In this chemically “clear” system that consist only of pore solution, chloride ions and inhibitors, corrosion inhibitor 2 showed better efficiency than inhibitor 1. On the other hand, when these two inhibitors were added in grout mixture, inhibitor 1 showed better efficiency. Since there were other admixtures besides corrosion inhibitors added into the grout mix to enhance other important properties of high performance grout, authors are of opinion that more research has to be performed to investigate compatibility and effect of different admixtures when together added into the grout.

Results of this work show that the influence of grout quality (physical protection) on corrosion protection of steel in grout is very high and that by designing high performance grout that has good properties in fresh and hardened state it is possible to lower the risk of corrosion and damage of prestressed concrete structures induced by corrosion.

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